19. The Anderson Localization in Metallic Films(Experiments,II Two Dimensional Systems)

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In this article, we present a quick review of recent experimental works on the Anderson localization and the electron-electron interaction effects in metallic films.

Soon after the theory by "gang of four"[1)] in 1979, the predicted lnT dependence was observed by Dolan and Osheroff[2)] in their films of Au-Pd. Since then, the theories and the experiments made surprisingly rapid progress and the study is now being extended to wider fields such as superconductivity and strong localization.

We summarize here the convention of notations which appear in the following.

τ_0 : elastic scattering time.

τ_ε : inelastic scattering time which is supposed to be $\tau_\varepsilon \propto T^{-P}$.

τ_{so} : spin orbit scattering time.

τ_s : magnetic scattering time.

F : shielding factor for electron-electron Coulomb interaction.

α_T^L and α_T^I : coefficient of lnT in temperature dependence of conductivity due to the localization and that to the electron-electron interaction.

From experimental point of view, the most important is to prepare good samples. The samples should be thinner than ~ 100 Å to assure the 2-dimensionality. They also should be considerably resistive, $\gtrsim 100\,\Omega$, to make it possible to measure expected small change in conductivity with reasonable accuracies. Pd and Pt were chosen because these form very thin continuous film when vacuum deposited.[2,4,10)] Alloying were employed to get higher resistivity. For Mg, Au etc., cold substrate were used to obtain continuous films.[11,15,19)] For Cu[3,7)] Ni and Mn films,[16)] Cu based films[13)] and some of Zn films,[22)] a new technique was used: it takes the advantage of the phenomenon, which is unfavourable in general, that the very thin film evaporated onto room temperature substrate forms isolated islands instead of a continuous film. After slightly oxdizing the first sheet of islands another sheet of islands were deposited. Repeating this process three times (or twice, depending on the material) a continuous and very resistive film could be obtained. The resistivity could be changed in several orders of magnitude by controling the oxidation degree without effecting the their parameters. Further, by changing the material of the last sheet of islands, some parameters such as the strength of spin-orbit interaction could be selectively changed.

The measurements of conductivity are rather conventional. To now, the temperature down to 10 mK and the magnetic field up to 13 T have been used. The measuring currents are mostly dc and sometimes very low frequency. High frequency measurement at microwave region has not been performed so far. Non-ohmicity was studied both theoretically (see the article by T. Tsuzuki in this report) and experimentally. However, because it is very hard to exclude the possibility of heating-up of samples, no conclusive results has been obtained in experiments.

Following the first report by Dolan et al., the lnT dependence of sheet conductivity $\sigma_{\square}(T)$ in much wider range of temperature was observed in Cu films[3] (Fig. 1). Similar lnT dependence was observed in Pt,[4] Pd,[4,5] Cu.[6] For all of these measurements, the coefficient of lnT term α_T was very close to $\frac{e^2}{2\pi^2\hbar}$ as was predicted by "gang of four". Therefore, it was believed that all these lnT were due to the localization effects at the time.

However a serious difficulty was pointed out when the α_T in Cu film was found not to change in magnetic field of up to 6 T.[7] According to the localization theory, 6 T was large enough to suppress the temperature dependence of $\sigma_{\square}$ completely. By this result, it was suggested that the lnT dependence arose from the electron-electron interaction[8] but not from the localization.[9] Later measurements in Pt film in high magnetic field[10] also suggested the same mechanism.

Besides the T dependence, the magnetic field dependence was found to be satisfactorily explained by the localization theory which takes the spin-orbit interaction into account.[7,11,12] Especially, the effect of spin orbit interaction was clearly demonstrated in composite samples of Cu-Cu, Cu-Ag and Cu-Au.[13] These samples consisted of two layers of Cu fine particles and the last layer of Cu, Ag and Au. Because these three elements are isoelectronic, only the strength of spin-orbit interaction was varied. By using the values of τ_0 and τ_ε which were determined by fitting in the sample of Cu-Cu, the results for Cu-Ag and Cu-Au were satisfactorily reproduced by adjusting only τ_{so}. The values of τ_{so} thus obtained for three films were quite reasonable (Fig. 2). By fitting the $\Delta\sigma(H)$ at various temperatures, the values of the temperature dependence of τ_i were determined. Assuming $\tau_i \propto T^{-P}$, P was found to be very small as $\sim$ 0.2 for Cu films.[13] This suggested that the observed lnT dependence was mainly due to the interaction effect. This was consistent with the result that α_T did not depend strongly on the magnetic field. In the other samples than Cu, such as Pd[14] and Pt,[10] the values of P were also very small. On the other hand, the interaction effect in the field dependence was found to be also small; F were as small as 0.1.[13] This small value of F also suppressed the effect of magnetic field through the spin-orbit interaction and of the Zeeman splitting,[8] and resulted in an field-insensitive α_T^I.

The role of τ_s, the spin scattering time, was first measured in Fe coated Mg films,[15] more systematically in Cu-Mn alloy films and in Ni and Mn films[16] as the extremely magnetic cases. For the films magnetically dirtier, the field dependence became weaker, being consistent with the localization theories (Fig. 3). The value of α_T stayed unaffected by the field as expected from the interaction mechanism. It was pointed out that the small value of P observed in Cu, Pd and Pt might be attributed to some paramagnetic centers in the films. Even if $\tau_\varepsilon \propto T^{-P}$, the effective rate to determine the amplitude of lnT through the localization mechanism is given as the sum of τ_ε^{-1} and $(\tau_s/2)^{-1}$.[12] Therefore, when τ_ε is much longer than τ_s, α_T^L, which is proportional to P, becomes zero because τ_s is usually temperature independent. Actually, in Cu, Ag and Au, films P = 1 $\sim$ 2 was observed at higher temperatures where τ_ε is expected much shorter than τ_s[17,18] (Fig. 4). In the films of Mg[19] and Bi,[20] the values of 1 $\sim$ 2 for P were observed even at low temperatures, probably because that no impurity could be magnetic in these materials.

In Bi films the total α_T, which is the sum of α_T^L and α_T^I, was observed to increase when the magnetic field was applied.[20] This result was consistent with the negative sign of α_T^L for the strong limit of the spin-orbit interaction; in strong field α_T^L becomes zero regardless of its sign. The reason why it was observable in Bi, but in Au, Pt or Pd, is that in the latters $\alpha_T^L \sim 0$.

The other properties such as the cross-over from 2 to 3 dimension,[21] the effect of the field parallel to the films[14] and the electric field effects[10] were also studied.

At present, as far as the nomal metal films in weakly localized region are concerned, the understandings of localization and interaction effects seem to be well established both theoretically and experimentally. The next field to be studied may be the superconductivity and the strong localization. The superconductivity, in a naïve sense, contradicts the localization, and at the same time has the same origin as the interaction effects. The measurements done in Zn films[22] showed that the superconducting transition temperature T_c dropped linearly with the increase of sheet resistance, and that the curves H_c vs. temperature had upward curvatures (Fig. 5). These results were quantitatively consistent with the theories[23] which corresponded to the higher order corrections to the Anderson theorem for dirty superconductors.

Some activation type behaviors in very resistive films were reported.[3,24,25) Nevertheless no systematic studies has been done in strongly localized regime.

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Figure Captions

Fig.1 The temperature dependence of conductivity σ in Cu films.[3,24] The variation is well fitted to $\sigma_{\square}(T) = \sigma_0 + \sigma_1 \ln T$ where σ_1 is very close to $e^2/2\pi^2\hbar$.

Fig.2 The magnetic field dependence of conductivity in Cu, Cu-Ag and Cu-Au films[13] with $\sigma_{\square} \simeq$ 2mmho. The curves in the figures are the fitting to the theory.[12] τ_0(= 9.5 x 10^{-14} sec), τ_ε(=2 x 10^{-12}sec) and D(=1.9 x 10^1cm^2/sec) are common for all three and τ_{so} are chosen to be 2.8 x 10^{-12} sec for the Cu film, 1.5 x 10^{-12} sec for the Cu-Ag film and 2.8 x 10^{-13} sec for the Cu-Au film.

Fig.3 The magnetic field dependence of conductivity in Cu-Mn alloy films with $\sigma_{\square} \simeq$ 2 mmho.[16] No.1 is pure Cu and the concentration of Mn increases with the the sample number from 0.1 to 12 % as shown below in Table 1. The results are fitted to the theory[12] with the parameters, τ_{so} = 2.8 x 10^{-12} sec, τ_ε = 2 x 10^{-12} sec and others are given in Table 1. Here we assume D and τ_0 is proportional to $\sigma_{\square}$. The value of τ_s are varied from 2 x 10^{-10} sec to 3.3 x 10^{-13} sec to get best fits.

Fig.4 The temperature dependence of the energy relaxation time τ_ε' in Cu films[13,18] The values of τ_ε' are deduced from the fitting of the magnetoconductance at fixed temperature to the theory disregarding the influence of τ_s.

Fig.5 The superconducting transition temperature vs. sheet resistivity in Zn films [22]. The solid line represents the theoretical results with parameters,

T_c in pure material ; T_{c0} = 1.02 K,

The Fermi energy ; E_F = 2.68 x 10^{-19} J.

The samples were prepared by two methods, but the results have no systematic difference, implying that suppression of T_c is dominated only by τ_0.

Table 1 List of Cu-Mn films. $\sigma_{\square}(0)$'s and parameters are given.

[Cu-Mn]	$\sigma_{\square}(0)$ (mmho)	D (x 10 cm^2/sec)	τ_0 (x 10^{-14}sec)	τ_s (x 10^{-12}sec)	Mn concentration (at%)
No.1	3.327	1.2	4.0	200.	< 10^{-3}
No.2	3.093	1.1	3.7	60	0.1
No.3	2.548	0.9	3.1	8.5	0.3
No.4	3.148	1.1	3.7	2.5	0.9
No.5	1.586	0.6	2.0	1.4	3.3
No.6	2.587	0.9	3.1	.33	12.

Fig.1

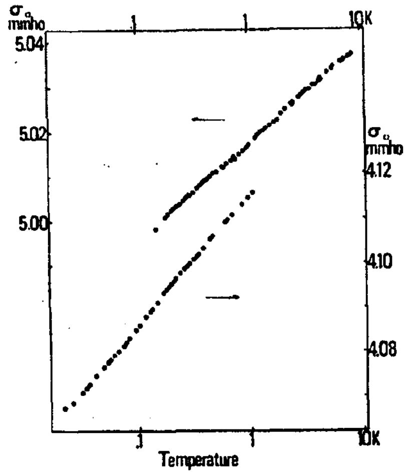

Fig.2(a)

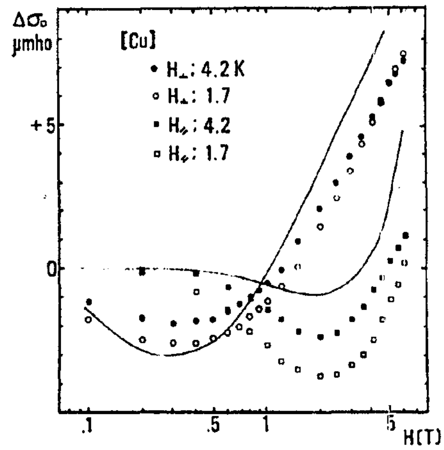

Fig.2(b)

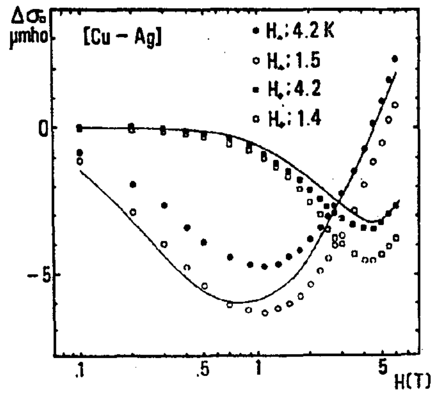

Fig.2(c).

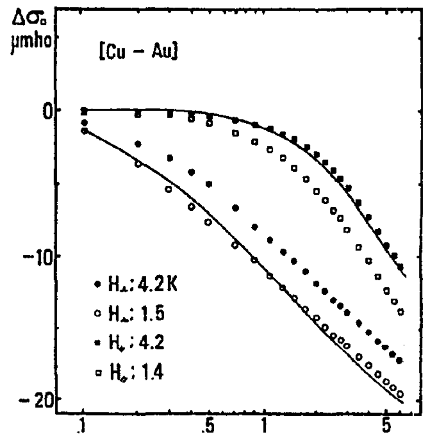

Fig.3

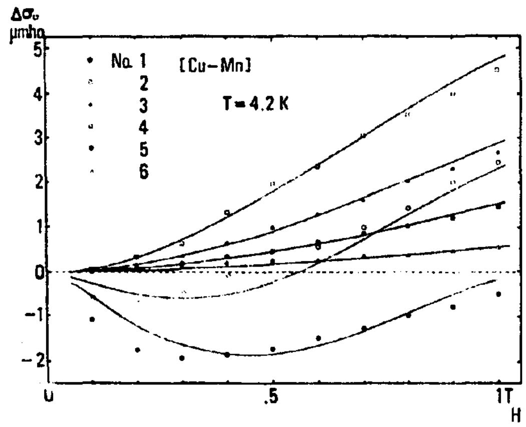

Fig.4

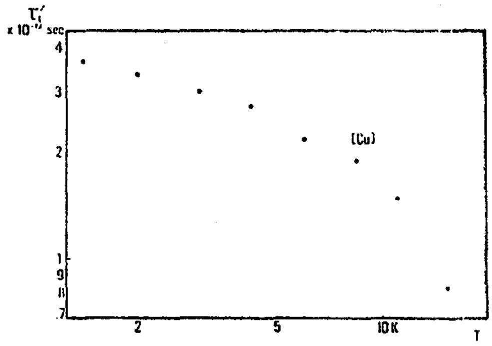

Fig.5